Ch. 13, Vol. 2

Effort-Based Decision Making

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Introduction

Over the years, laws of decision-making have addressed specific scenarios or forms of decisions undertaken by different organisms. Two approaches comprise normative and descriptive theories (Morelli et al., 2022). Normative theories take a top-down approach, describing what rational agents ought to do to maximize gains and minimize losses when facing possible actions, each associated with an outcome and with a given probability that it will occur. In contrast, descriptive theories are based on the observation that in controlled experiments and real life, agents frequently violate the laws and predictions made by normative theories. In fact, descriptive theories take a bottom-up approach, aiming to describe how agents actually behave and attempting to explain why they often make decisions that seem less than optimal or less rational (Kahneman and Tversky, 2013; Mishra, 2014; Moreira, 2018).

Different forms of decision-making have been under scrutiny (Platt and Huattel, 2018; Trimmer et al., 2011), under stress (Starcke and Brand, 2012), and under time pressure (Edland and Svenson, 1993). Decision-making often happens in a social context rather than in isolation (Rilling and Sanfey, 2011; Sanfey, 2007). Such research has proven extremely valuable in advancing our knowledge pertaining to decision-making and social problem solving (cf. Barbey et al., 2014). Classic accounts of decision-making under conditions of uncertainty predict that individuals act in a way that maximizes the final utility of their actions (i.e., increases rewards obtained). Under this framework, people decide whether to acquire new information before

making a final decision based on a cost-benefit analysis. Will the new information increase the expected utility as compared with deciding without it? (Juni et al., 2016). However, classic accounts of decision-making have tended to overlook the cognitive effort/cost associated with collecting new information. Petitet et al. (2021) demonstrated how the cognitive effort spent while collecting new information is a crucial cost traded against reward during active information sampling. This is just one example showing how humans and animals (e.g., non-human primates) integrate the processing of past and expected cognitive and physical efforts in the computation of a cost-benefit analysis when deciding between several possible options. Inclusion of cognitive effort in decision-making models thus helps create a more complete picture of the actual complexity involved in how organisms make decisions in several types of scenarios.

Effort-based decision-making specifically refers to those decisions that involve evaluating whether a certain goal is worth the physical (e.g., motor action) or cognitive (e.g., computational) effort necessary to achieve it (Shadmehr and Ahmed, 2020; Westbrook and Braver, 2015; Yoon et al., 2018). This line of research started from the early evidence that animals' choices are not a mere function of the amount of the expected reward and that the cost of the associated action plays an important role in the decision-making process (Stephens and Krebs, 1987). For instance, rats and monkeys weigh the number of responses necessary to get a reward (Walton et al., 2006) and birds' choices depend on the metabolic costs of the available options (Bautista et al., 2001). In other words, the decision-making process involves a cost-benefit computation in which motivation necessarily activates and directs behavior to obtain a specific goal (Bailey et al., 2016); but when several response options are available, the cost (or

effort) of each option is weighed against the anticipated benefit and the choice will land on the one that maximizes this trade-off (Bailey et al., 2016).

Daily life decisions are modulated by the amount of effort required for selecting, performing, and monitoring the necessary actions to achieve a goal (Gallivan et al., 2018; Scott, 2004; Todorov, 2004). For example, regarding the decision to drink a glass of cool water, we can intuitively imagine how the same series of actions (i.e., heading to the refridgerator, pouring the water into a glass, etc.) that can lead to one's goal (drinking water) will be performed very differently after a short walk, as opposed to after having just completed a lengthy marathon run. In the latter case, water is more valuable, and the overall drinking process will be performed more vigorously. Similarly, if we have to transport a large number of glasses of water up a staircase, is it worth carrying a few glasses at a time, but going back and forth two or three times (increasing energy expenditure but decreasing the risk of breaking any glasses), or is it better to carry them all in one go on a tray (decreasing energy expenditure but increasing the risk of breaking the glasses)?

In this chapter, we provide a general overview of the concept of effort-based decision-making, and the scientific evidence pertaining to this topic. Also, we highlight the connection between physical effort (intended as the vigor response) and reinforcement learning in human decision-making. This chapter is organized into three main sections: 1) the first focuses on concepts of utility and foraging behavior, as historically relevant observations from which the study of effort-based decision-making have taken place; 2) the second disentangles the concepts of physical and cognitive effort and lays out the experimental evidence arising from both lines of research; 3) the third focuses on the interplay between effort-based decision-making and reinforcement learning by clarifying (a) how motivation for a reward can modulate physical

effort; (b) the extent to which response vigor has been conceived and used as a measure of physical effort; (c) the role of dopaminergic activity in response vigor; and (d) the interplay between Pavlovian and instrumental learning processes in the modulation of effort-based decision-making.

Foraging behavior and the concept of utility

Effort-based decision-making has been studied by a plethora of disciplines, from cognitive psychology to behavioral economics and computer science, all of which seem to be aligned on the idea that the computation of the cost-benefit trade-off can be represented by a so-called utility function (i.e., the benefit of each available choice is weighted against the cost required to achieve such a benefit, in order to select the one with the highest subjective value) [(rewards–effort) / time] (Shadmehr and Ahmed, 2020, 2021; Stephens and Krebs, 1987; Yoon et al., 2018). Historically, foraging behavior has been used as a typical "case study" in which the role of effort in decision-making can be observed inside and outside the laboratory.

When foraging, animals have to decide when it's worth to stop harvesting a specific site and when to move to another one to seek new food opportunities (Shadmehr et al., 2019; Sukumar et al., 2021). Intuitively, the expected behavior may be to fully harvest a specific site until no food is left and only then move to the next one. However, an apparently suboptimal behavior is frequently observed, that is, animals stop looking for food when the supply is diminishing, even if still available (Yoon et al., 2018). The optimal solution is conceived as the one that maximizes rewards acquired over time. This implies that abandoning some food may be worthwhile if the time can be better used to exploit other potentially more rewarding locations (i.e., locations with more food (Yoon et al., 2018). The general idea put forward is that the decision to harvest depends not only on the reward currently available but also on the expected cost, learned from the consequences of past actions (see marginal value theorem; Stephens and

Krebs, 1987). Thus, an animal might decide to abandon a current source of food if the time and effort required to consume it can be better invested in searching for a more rewarding site (Cuthill et al., 1990; Niv et al., 2007; Perry et al., 2016; Wang et al., 2013).

The idea behind the concept of utility is that, deciding how and where to spend one's effort is based on a trade-off between the anticipated costs and the benefits foreseen for any set of behaviors, choices, or simple actions. This concept, born from the study of simple foraging scenarios, subsequently has been applied to the broader field of decision-making (Camerer, 2011; Westbrook and Braver, 2015) in which it has been used to investigate and describe how much one values a particular good and/or is willing to work for it (Shadmehr et al., 2016). These scenarios can be seen as a special case for the application of the utility function (rewards–effort / time), in which the *effort* of the equation can consist of either the physical or cognitive costs associated with each decision. Next, we review the experimental evidence around the two constructs of physical and cognitive effort.

Physical versus cognitive effort

In the previous section, we saw that animal studies have laid out the basis for investigating the role of effort in decision-making in humans. Classical studies have focused on a type of cost that is intrinsic to the action performed to achieve a goal (i.e., its physical effort). Physical effort is intended as the expenditure of energy required to perform a given action, for instance, by changing the grip strength of a dynamometer (Bhuanantanondh et al., 2018), the angle of inclination of a treadmill, the amount of bar pressing (Walton et al., 2006). Another option has been to present the animal with multiple possible courses of action differing for their energetic demands (e.g., by inserting barriers in their path) and reward (Hillman and Bilkey, 2010).

Inspired by the literature on non-human animals, research on humans has mostly defined the effort involved in decision-making as the physical effort exerted for a given action. For

instance, the amount of force used to squeeze a handgrip force measure device (Cléry-Melin et al., 2011; Ettenberg, 1989; Fowler and Fowler, 1999), the number of key presses required to achieve a gain or avoid a loss (Gallistel and Gelman, 1992; McDowell, 2013; Porat et al., 2014), distance traveled (Gallistel, 2003), or time taken (Balsam and Gallistel, 2009; Balsam et al., 2010; Evenden and Ryan, 1996; McDowell, 2013). These studies suggest that, like non-human animals, humans tend to avoid spending effort, for instance by choosing the path that requires the fewest number of steps (Bitgood, 2006), or the sequence of reaching movements that minimize the metabolic cost (Alexander, 1997; Goble et al., 2007).

Physical effort is somewhat an intuitive and easy-to-operationalize measure, as it can be related to easily measurable variables such as metabolic costs (e.g., the amount of adenosine triphosphate utilized for muscle contractions; Russ et al., 2002; Stienen et al., 1995), or amount of oxygen uptake (Tseh et al., 2008), as well as performance parameters such as the distance covered, the amount of force exerted (Morel et al., 2017), or the speed exerted to accomplish a task on time. The rationale is that acting more quickly can help to obtain rewards more quickly but at the cost of more effort (Boureau and Dayan, 2011). To some extent, this corresponds to the cost associated with time in foraging scenarios, where the average utility is optimized per unit of time (Daw and Touretzky, 2002), and thus putting too little effort may imply that you get very little reward (Boureau and Dayan, 2011), but putting too much effort will decrease the value of the reward.

However, most decisions in everyday life present costs that are not just physical or metabolic, but also economic, social (such as social exclusion), emotional, and cognitive. Much like physical effort, we also intuitively know what cognitive effort is: we all know how different it feels to read a difficult scientific paper as compared to watching an action movie. Similarly, we

have an intuitive feeling that allocating cognitive resources is costly and one of these two actions clearly has a higher cognitive cost as compared to the other: engaging for a high period of time in a cognitively demanding task leads to a state of cognitive fatigue (Massar et al., 2018).
Many studies have implicated cognitive effort in a wide variety of phenomena, ranging from political preferences to clinical conditions such as depression, and schizophrenia (Culbreth et al., 2018; Hershenberg et al., 2016; Stevens, 2014; Tran et al., 2021). These studies have found some similarities and even a link between cognitive and physical effort. For instance, a study found that participants who show a stronger aversion to cognitive effort also show a stronger aversion to physical effort (Nishiyama, 2016). Moreover, there is increasing evidence that cognitive exertion and fatigue have a negative effect on physical activity behavior (Brown et al., 2020; Van Cutsem et al., 2017), however, this evidence is mixed (van As et al., 2021).

Just as with physical resources, humans have limited cognitive resources and need to be careful when deciding how to allocate them (Barbey et al., 2021; Kuo et al., 2009; Muraven and Baumeister, 2000). It has been largely accepted that, when confronted with different options, generally individuals show a preference for the one with the least cognitive cost (Chong et al., 2017; Kool et al., 2010). This idea has been summarized as, “people tend to act as ‘cognitive misers’ (Corcoran and Mussweiler, 2010), meaning that they are willing to waive a reward to avoid making the necessary cognitive effort (Westbrook et al., 2013; Westbrook and Braver, 2015)”. As influential as this idea has been, much like physical effort, individuals' decisions to exert cognitive effort depend on an interaction between rewards, cognitive costs, and time (Westbrook and Braver, 2015). Moreover, willingness to expend cognitive effort is highly variable among individuals. Some people tend to enjoy and even seek out effortful cognitive endeavors (Cacioppo et al., 1996; Westbrook and Braver, 2015; Westbrook et al., 2013). For

instance, someone may be enjoying a crossword puzzle, or someone may be completing a coding challenge just for enjoyment. It is also common for people to undertake highly effortful tasks to achieve a long-term goal (e.g., enrolling in a university course). Thus, different people have different "need for cognition", a stable personality trait that refers to people's tendency to seek out, engage, and enjoy effortful cognitive activities for their own sake (Cacioppo et al., 1996; Cacioppo and Petty, 1992).

Nevertheless, increasing experimental evidence shows that many non-human animals, as well as human children and adults, under certain circumstances will value a reward more if it requires effort (Inzlicht et al., 2018). This has often been exemplified as the "Ikea effect", which refers to the phenomenon that people like their furniture more when they have assembled it themselves or, in more general terms: successfully completing a laborious task can lead to a greater liking for the results of one's own labor (Norton et al., 2011). This does not only pertain to physical effort, but also cognitive effort. For example, Clay et al. (2021), provided evidence that even after a short period of experiencing effort-contingent reward, people begin to value effort positively and choose to engage in tasks requiring high-effort exertion in the absence of any extrinsic reward. In light of this evidence, recent studies have challenged the idea of humans as cognitive misers who avoid effort whenever possible and put forward a more comprehensive view that highlights how effort, both physical and cognitive, can be positively associated with reward (Clay et al., 2021; Inzlicht et al., 2018).

We now turn our attention to some differences between physical and cognitive effort. As opposed to physical effort, there is still a lack of consensus on how to define and operationalize cognitive effort. Westbrook and Braver (2015) pointed out that it is easy to conflate cognitive effort with motivation, task difficulty, cognitive control, and attention, because there are overlaps

between cognitive effort and these other cognitive properties. However, they are not the same. Some have attempted to explain cognitive effort in terms of depletion of limited metabolic resources. For instance, Gailliot and Baumeister (2007) proposed that enforcing self-control depletes large amounts of glucose and that self-control appears highly susceptible to glucose levels (e.g., self-control failures are more likely when glucose is low or cannot be mobilized effectively to the brain) (Gailliot and Baumeister, 2007). It is easy to see a parallel between physical effort and this proposal, however, this idea has been challenged by works showing little changes in glucose consumption following control-demanding tasks, such as two-digit arithmetic vs. recognizing a face (Kurzban, 2010; Westbrook and Braver, 2015). Other metabolic accounts have proposed that, rather than with the depletion of resources, cognitive fatigue is associated with a build-up of waste products, such as amyloid-β in the interstitial fluid (Holroyd and McClure, 2015). Alternative accounts, such as mechanistic, have operationalized cognitive effort in terms of information processing, for instance, in Shenhav et al. (2017), "*Effort is what mediates between (a) the characteristics of a target task and the subject's available information-processing capacity and (b) the fidelity of the information-processing operations actually performed, as reflected in task performance*". Overall, it is apparent that there is not much consensus as to how to define cognitive effort, and how to operationalize and measure the construct.

Although there is a strong consensus that physical effort is an intrinsic and unavoidable cost associated with the expenditure of energy required to perform a chosen action, cognitive effort is not so easily defined, as it certainly involves a purely cognitive element (e.g., working memory load) but can also present economic, social and emotional components which may not act in the same way, thereby possibly explaining the high heterogeneity of findings.

Nevertheless, a common feature is that although higher physical or cognitive demands can help to achieve a goal, the higher cost associated with both kinds of effort also enters the equation in both human and non-human decision-making (Boureau and Dayan, 2011; Westbrook and Braver, 2015). As discussed above, we have provided an overview of the basic concepts of utility, physical and cognitive effort, and how they have been operationalized in the experimental literature. There are several angles from which effort-based decision-making could be further examined. Next, we focus on the interconnections between physical effort and reinforcement learning in human decision-making.

Effort-based decision-making and reinforcement learning

Reinforcement learning concerns how the rewards and punishments (reinforcers) that we encounter in daily life can encourage or discourage choices or actions. The anticipation of reinforcers has many implications in the computation of the cost-benefit tradeoff that guides effortful decision-making. The relationship between effort and reinforcer value is bidirectional. More rewarding options are preferred when the effort involved is comparable, and such preference can be switched if a lower reward is available for a smaller effort (Ivry, 2013; Xu-Wilson et al., 2009). However, effortful actions can also enhance how much we like or prefer a given food (Johnson and Gallagher, 2011) and how much we are willing to choose effortful actions in the future (Eisenberger et al., 1989; Friedrich et al., 2005). For instance, increasing the amount of labor required to utilize a purchased good can increase its perceived value (Norton et al., 2011). Moreover, vigor can be actively increased (Bailey et al., 2016; Pessiglione et al., 2007) or decreased (Pizzo et al., 2009; Tanno et al., 2014) to adjust to task requirements and obtain a higher reward.

Reward modulates physical effort

Although studied separately for a long time, decision-making and motor control are closely tied together. Increasing evidence points to the idea that factors that affect choices, such as reward and effort, also affect movements (Shadmehr and Ahmed, 2020). For example, actions toward the preferred outcome are faster than those performed toward less preferred items (Gill et al., 2020; Shadmehr and Ahmed, 2020).

When multiple choices are available, a specific utility is assigned to each potential action, depending on the reward at stake and the effort required to perform that action. Such effort is estimated based on how that action will be performed (i.e., its sequence of motor commands such as speed and trajectory; Shadmehr et al., 2016a). Both the response and the motor sequence eventually chosen are those with the highest utility (i.e., the ones that minimize the effort and maximize the reward). An action that is associated with a high utility is not only preferred but is also performed faster to increase the amount of reward collected in a given period of time (Gordon et al., 1994; Kawagoe et al., 1998; Xu-Wilson et al., 2009).

To increase the utility, the physical effort must be consistent with the choice. In general terms, it is not optimal to spend more effort to be faster, especially if rewards are low (Gordon et al., 1994; Shadmehr et al., 2016a, 2016b; Summerside et al., 2018). However, for larger rewards, being faster - and, thus, spending more effort - can save time to look for other rewards (i.e., increase the capture rate and reduce the discounted value of the reward; Shadmehr and Ahmed, 2020). Accordingly, both humans and animals have been repeatedly reported to act faster (both in terms of higher velocity and shorter reaction times) to obtain higher rewards (Haith et al., 2012; Kawagoe et al., 1998; Mosberger et al., 2016; Opris et al., 2011; Reppert et al., 2015; Sackaloo et al., 2015; Summerside et al., 2018; Takikawa et al., 2002).

Vigor as a measure of physical effort

The concept of vigor (primarily intended as the force or speed) of action has gained attention as a useful parameter to study, on a continuous scale, how the brain controls behavior and estimates the amount of effort that it is willing to expend to reach its goals (Shadmehr et al., 2019). One of the main reasons for attention to vigor is that it seems to be closely related to the concept of utility, to the extent that the vigor of action is intended as a way to directly infer its utility (Shadmehr et al., 2019). This idea found its roots in the evidence that vigor and utility are modulated by the same factors, such as reward magnitude and deprivation. Not only does the prospect of greater reward invigorates movements, but vigor also decreases as the reward is further away to be achieved (Bailey et al., 2016; Shadmehr et al., 2019).

Evidence shows that the speed of several movements (i.e., reaching, walking, or eye movements) increases as a function of reward characteristics (Haith et al., 2012; Kawagoe et al., 1998; Milstein and Dorris, 2007; Rigoux and Guigon, 2012; Sackaloo et al., 2015; Shadmehr et al., 2016b; Summerside et al., 2018; Takikawa et al., 2002; Thura et al., 2014; Xu-Wilson et al., 2009; Yoon et al., 2018), and declines as a function of effort (Bobbert, 1960; Gordon et al., 1994; Minetti et al., 2003; Reppert et al., 2018; Schweighofer et al., 2015; Shadmehr et al., 2016b; Stelmach and Worringham, 1988; Wang et al., 2021; Wickler et al., 2000). For instance, saccadic eye movements present shorter latency, higher speed, or greater peak velocity for larger rewards (Milstein and Dorris, 2007; Thura et al., 2014). Similarly, reaching movements toward more valuable rewards are faster (Sackaloo et al., 2015; Summerside et al., 2018).

In parallel, movements toward high-effort stimuli are characterized by a longer latency and lower speed (Shadmehr et al., 2019). For example, reaching movements present increased reaction time as the target distance increases (Reppert et al., 2018) and are faster when the arm moves in directions with lower mass (Shadmehr et al., 2016b). Moreover, movement vigor also

shares some of its dynamics with foraging-like behaviors (Constantino and Daw, 2015; Guitart-Masip et al., 2011; Niv et al., 2007; Wilson et al., 2015; Yoon et al., 2018). In a series of experiments, Yoon and colleagues (2018) showed how subjective harvest duration and movement vigor varied according to what was predicted by the optimal foraging theory: a site is harvested when the effort equals the negative of the capture rate and is abandoned when gains equal the capture rate.

Role of dopamine

Niv et al. (2007) developed a computational model of optimal action selection that accounts for the role of dopamine in determining the vigor of responding within a reinforcement learning framework. This model interprets vigor as a manifestation of effort expenditure in the time domain (Kurniawan et al., 2011). The general idea is not too far from that of optimal foraging and utility function, in that the optimal vigor (here intended as the latency) of a choice is assumed to be the one that maximizes the amount of reward per unit of time. Thus, the optimal latency of a choice is inversely proportional to the average reward rate. The authors provide a series of evidence in support of the idea that this information is specifically coded by tonic levels of dopamine, as opposed to phasic dopaminergic activity linked to appetitive prediction errors. This model has the advantage of reconciling with psychological theories about dopamine's role in energizing responses by taking into account the fact that such dopaminergic activity can be modulated by motivational factors, such as the value of the outcome. In this view, the cost-benefit trade-off entailing the vigor with which a choice is expressed embodies a continuous-valued decision about how much effort to exert given the benefits at stake (Niv et al., 2007).

Pavlovian and instrumental interplay in the modulation of effort

As discussed above, rewards (or punishments) can directly influence how we learn and perform actions by determining the amount of benefit (i.e., gaining rewards or avoiding punishments -

associated with each choice). However, another (perhaps more indirect) source of influence is exerted by means of a cue-guided Pavlovian modulation of the effort, and thus, the cost (associated with the instrumental action performed to express such choice; aka, cue-guided choice).

From a cost-benefit perspective, effortful actions are always less optimal in terms of energy consumption. Actions should, thus, not be invigorated unless necessary to complete the task (Kool et al., 2010). If obtaining a reward or avoiding punishment is not contingent upon the vigor of the action, one shall save energy by using the minimum amount of effort possible. Nevertheless, interactions between Pavlovian cues and instrumental actions prospect a different scenario. The vigor with which humans execute instrumental actions can be modulated by environmental stimuli anticipating appetitive or aversive consequences (i.e., Pavlovian cues). This effect can be experimentally observed in the so-called Pavlovian-to-Instrumental Transfer (PIT) effect, which reflects the ability of a Pavlovian conditioned stimulus (CS) (i.e., a cue paired with a reinforcer) to increase the likelihood or vigor of an instrumental response independently paired with a reinforcer (Cartoni et al., 2016; Gerlicher and Kindt, 2020; Holmes et al., 2010; Mahlberg et al., 2019). In this paradigm, instrumental response–outcome (R–O) associations and Pavlovian stimulus–outcome (S–O) associations are independently acquired in two separate task phases.

Specifically, in the first instrumental learning phase, one or more actions are reinforced with rewarding outcomes (such as the delivery of food or termination of an aversive loud noise). Here, the acquisition of the instrumental R-O association is indicated by the increased performance of the reinforced action (Starita and di Pellegrino, 2018). In the second Pavlovian learning phase, intrinsically neutral cues acquire appetitive or aversive value by being paired

with a reward or a punishment, using the same or similar outcomes presented in the first phase (e.g., the same or similar food or aversive loud noise). Here, the acquisition of the Pavlovian S-O association is most commonly assessed by changes in subjective reports of valence or changes in psychophysiological response to the presentation of the cue (Battaglia et al., 2020; Garofalo et al., 2015, 2017; Starita et al., 2016, 2019a,b). Crucially, Pavlovian cues are never directly matched with a response, thus, no direct stimulus-response link is ever established. In the third phase, task-irrelevant Pavlovian cues are presented while the participant is required to perform the same instrumental actions previously trained. A PIT effect is observed if the Pavlovian cue triggers responses previously paired with the same (outcome-specific transfer) or a similar (general transfer) outcome, even though the Pavlovian cue and the response were never associated. Crucially, the PIT effect is observed even in absence of current reinforcers (i.e., under extinction), thus when responses do not lead to any reward. This kind of behavior is also referred to as cue-guided or cue-triggered choices (Garofalo et al., 2019, 2021; Keistler et al., 2015).

Although with some exceptions (Hogarth et al., 2014; Lovibond and Shanks, 2002; Mahlberg et al., 2019; Mitchell et al., 2009; Seabrooke et al., 2016), the PIT effect has been generally interpreted as the ability of a Pavlovian cue to transfer its motivational properties and bias choice by invigorating – and thus spending more effort on some responses rather than others (Corbit and Balleine, 2015; Lovibond, 1983).

How appetitive cues modulate effort

Instrumental behavior to obtain desirable outcomes can be characterized in several ways. Most studies into human Pavlovian-to-Instrumental Transfer quantified the invigoration operated by Pavlvoian cues in terms of increased response rate (Corbit et al., 2007, 2016; Corbit and Balleine, 2011; Freeman and Ambady, 2010; Garofalo et al., 2019, 2020, 2021; Guitart-Masip et

al., 2011; Keistler et al., 2015; Mendelsohn et al., 2014; Watson et al., 2014). For example, in a series of behavioral studies, food-associated Pavlovian cues were found to increase the number of responses associated with the same or motivationally similar foods (Garofalo et al., 2019, 2020; Hinojosa-Aguayo and González, 2020; Quail et al., 2017; Watson et al., 2014). This effect also appeared to be related to the prefrontal cortex and dopaminergic activity (Garofalo et al., 2021; Soutschek et al., 2018). Similar results were also found for monetary rewards (Garofalo and di Pellegrino, 2015; Jeffs and Duka, 2017; Lehner et al., 2017; Nadler et al., 2011; Schad et al., 2020; Talmi et al., 2008). Along the same line, other studies have reported that presentation of the Pavlovian cue was related to faster reaction time (Freeman et al., 2014).

One group of studies utilized a more direct measure of physical effort by quantifying its vigor on a continuous scale (Shadmehr), namely as the amount of handgrip force (i.e., squeezing) used to express the biased choice. Among these, Lehner et al. (2017) used a bimanual grip force task to observe how participants distributed forces between hands associated with different response options. They found that participants reached maximal hand contraction when a reward-associated cue was presented in the background, as compared to a neutral cue. The strength of this effect was correlated to the subjective value attributed to the reward (Garofalo and di Pellegrino, 2017). Da Costa et al. (2020) trained participants to apply force to a handgrip to win money from computerized slot machines and found the maintenance of effortful behavior in the presence of a Pavlovian cue - both in terms of higher response frequency and greater force - even when participants were likely fatigued (da Costa et al., 2020). De Tommaso et al. (2018) observed that while the incentivizing power of a Pavlovian cue associated with beverage reward in terms of the number of responses endured until the end of the task, the force (handgrip pressure) of the instrumental response declined in time, regardless of the state (thirsty vs

satiated) of the participant. Talmi et al. (2008) observed that the frequency of hand grips increased in the presence of a Pavlovian cue paired with money gains was associated with increased blood oxygenation level-dependent (BOLD) signal in the central portion of the nucleus accumbens using functional magnetic resonance imaging (fMRI) (Talmi et al., 2008).

The invigorating effect of food-associated Pavlovian cues on grip force (Ziauddeen et al., 2012) and response rate (Garofalo et al., 2020) have been observed when the stimuli were subliminally presented. These results highlight the subtle influence that environmental cues can exert on how we modulate effort in our decision-making even when these stimuli are not consciously perceived (Garofalo and di Pellegrino, 2017).

Additionally, in appetitive contexts, the influence of Pavlovian cues onto instrumental actions has also been related to human sign-tracking behavior (Garofalo and di Pellegrino, 2015), a learning style characterized by the tendency to attribute particularly high incentive salience to Pavlovian reward-associated cues. Sign-tracking behavior has been mainly investigated in non-human animals where it has been associated with maladaptive behaviors such as addiction or impulsive conduct (Flagel et al., 2008; Robinson and Flagel, 2009; Tomie et al., 1998). The general idea is that, in sign-trackers, Pavlovian cues become a powerful source of motivation over behavior (Flagel et al., 2011). Relatedly, several studies supported the involvement of the mesolimbic dopaminergic system in the emergence of sign-tracking behavior and reported increased levels of dopamine in the nucleus accumbens correlated with the vigor with which the Pavlovian conditioned response is performed (Flagel et al., 2007, 2008).

How aversive cues modulate effort

Boureau and Dayan (2011) proposed an orthogonal model that disentangles the valence of an outcome - reward vs punishment - from the nature of the action required to obtain that outcome - invigoration vs inhibition (Boureau and Dayan, 2011; Ikemoto and Panksepp, 1999). The authors

propose a direct association between rewarding valence and invigorated actions – mediated by dopamine – as opposed to a direct association between punishment and inhibition – mediated by serotonin (Boureau and Dayan, 2011). According to this view, while rewarding outcomes are more readily associated with invigorated actions, aversive outcomes are more readily associated with action inhibition (Boureau and Dayan, 2011). Thus, pigeons and chickens have a hard time learning to stop pressing a lever in order to receive food (Hershberger, 1986; Lovibond, 1983; Woods and Bouton, 2006). Such a response has been proposed to reflect freezing, although it does not seem to be associated with reduced muscle tension (Gerlicher and Kindt, 2020).

More sophisticated tasks in humans showed that participants are better at responding promptly to a "go" signal than inhibiting an action to a "no-go" signal when the goal is to win money (Guitart-Masip et al., 2011) and are more likely to succeed in avoiding monetary loss when action inhibition is required, rather than action emission (Guitart-Masip et al., 2011). Similarly, "go" responses are favored when it is possible to win money, while "no-go" responses are favored when there is a chance to lose money (Guitart-Masip et al., 2012). In the same vein, fMRI studies showed that the amygdala and the nucleus accumbens were associated with behavioral inhibition by aversive Pavlovian cues (Lewis et al., 2013). Moreover, dopamine depletion reduced the impact of appetitive, but not aversive, Pavlovian stimuli on instrumental responses (Hebart and Gläscher, 2015) while serotonin inhibition was associated with the opposite pattern (Geurts et al., 2013), suggesting that the invigorating or inhibiting effect of Pavlovian appetitive versus aversive cues on instrumental responses relies on different mechanisms.

Such a basic relationship between action invigoration-reward and inhibition-punishment, however, does not capture the whole picture, as more complex interactions between these four

elements are possible (Boureau and Dayan, 2011; Gerlicher and Kindt, 2020). Cessation of an aversive outcome, for example, can have an appetitive flavor, as it implies safety and can serve as a positive reinforcer of actions (Boureau and Dayan, 2011; Gerlicher and Kindt, 2020),

Transposed onto the influences that Pavlovian cues can exert on the vigor of a choice (i.e. PIT effect), while some classical studies focused more on conditioned facilitation, i.e. the idea that aversive Pavlovian cues favor a motivational state that facilitates avoidance responses (Corbit and Balleine, 2011, 2015), others pushed more towards the evidence for conditioned suppression (i.e. the inhibitory effects that aversive Pavlovian cues exert on appetitive responses) – for example, responses directed to obtain a reward (Dickinson and Balleine, 2002). More recent studies on humans reported conditioned suppression when the reward amount was low (Allcoat et al., 2015; Greville et al., 2013), but not when the reward at stake was more valuable (Hebart and Gläscher, 2015; Xia et al., 2019).

Overall, aversive Pavlovian cues can potentiate instrumental responses that lead to the avoidance of an aversive outcome (i.e., conditioned facilitation of avoidance; Campese et al., 2013; Heinz et al., 2001). Garofalo and Robbins (2017) found a task-independent increase in the force exerted on a handgrip moved towards the left or the right to prevent incoming aversive noises when participants were presented with an aversive scenario (Garofalo and Robbins, 2017). Trick et al. (2011) found a higher number of avoidance responses (space bar presses) corresponding to the presentation of visual cues which predicted the occurrence of an aversive noise with a 90%, 50%, or 10% probability. Similarly, Krypotos et al. (2011) and Nadler et al. (2011) found an increased number of button presses associated with the cancellation of an aversive outcome when participants were presented with an aversive Pavlovian cue. Xia et al. (2019) found that aversive Pavlovian cues induced conditioned facilitation (increased response

rate) of avoidance withdrawal responses, but no conditioned suppression of approach responses. In line with this complex interpretation of the interplay between action and outcome valence, it was found that while dopamine appears to be necessary for active avoidance and startle reaction to aversive stimuli (Fadok et al., 2009; Maia, 2010; Moutoussis et al., 2009), serotonin also appears to play a role in action inhibition in appetitive contexts (Fletcher, 1993; Gruninger et al., 2007; Harrison et al., 1997). Moreover, shorter reaction times following the presentation of a Pavlovian stimulus paired with money loss were found to be in direct association with serotonergic modulation (Crockett et al., 2012).

Huys et al. (2011) found that Pavlovian cues can act as facilitators as long as their valence is coherent with the nature of the action: appetitive cues promote approach and inhibit withdrawal while aversive cues promote withdrawal and inhibit approach despite the task requirements (e.g., even when the withdrawal is appetitively motivated, it is still inhibited by appetitive Pavlovian stimuli and enhanced by aversive ones). Therefore, if the nature of the Pavlovian cue is inconsistent with the action required (i.e., appetitive cue – withdrawal action or aversive cue – approach action), this can interfere with learning.

Summary and Conclusions

This chapter has examined the role of effort in decision making thereby providing a general overview of the concepts and scientific evidence that nurtured this field of research, from the early concepts of foraging behavior and utility function to more recent experimental studies about physical and cognitive effort. We have highlighted the connection between physical effort (intended as response vigor) and reinforcement learning in human decision-making.

Early evidence from animal studies have shown that, when deciding on a course of action, animals evaluate not just the expected reward, but also the costs associated with each possible action (Stephens and Krebs, 1987). This simple observation has led to a plethora of

studies spanning several disciplines, such as cognitive psychology, behavioral economics, and computer science, which converge on the idea that the cost-benefit trade-off can be represented by a formula, referred to as utility function, in which the benefit of each available choice is weighted against its costs in order to select the one with the highest subjective value (Camerer, 2011; Shadmehr and Ahmed, 2020; Yoon et al., 2018). As discussed, such costs can be intrinsic to the actions themselves and can come in different forms, such as physical or cognitive efforts. Classical studies on physical effort have shown that in most scenarios, humans and animals act in a way that is consistent with the law of less work. If all other factors are held constant, they will choose the action that minimizes effort expenditure. More recent studies also provided evidence of a connection between physical and cognitive effort, in that (1) they influence each other (Nishiyama, 2016), and (2) there is a parallel between the tendency to minimize or avoid both cognitive and physical demands (Kool et al., 2010). Finally, effort-based decision-making in the context of reinforcement learning paradigms shows not only that the expectation of a reward can modulate effort expenditure, but also that the effort with which humans execute instrumental actions can be modulated by environmental stimuli anticipating appetitive or aversive consequences. Crucially, these studies point to a behavior that can be regarded as sub-optimal, if presenting a cue associated with punishments or rewards can invigorate actions even when task-irrelevant (i.e., not required to obtain the reward or to avoid the punishment), the higher effort exerted may be unnecessary.

Many research issues remain to be addressed. For example, an important and still debated aspect concerns how to best operationalize and measure both forms of effort. Recent advancement within the field of physical effort has come from the evidence of a link between decision-making and motor control, which has led to conceptualizing “vigor” as a possible

measure of physical effort. This concept has rapidly gained much interest, probably due to its flexible application in many fields, ease of measurement, potential use as an implicit proxy of utility, and the possibility to quantify effort on a continuous scale (Shadmehr et al., 2019). Moreover, several open questions remain unanswered: which psychophysiological measure (e.g., skin conductance, heart rate, muscle contraction, etc.) can best track effort both on a physical or cognitive level; whether the same or separate neural systems mediate the two; the precise role played by dopamine and its neural substrates in the modulation and perception of effort; whether personality traits can modulate the weight of effort in individual choices (Kurniawan et al., 2011; Walton and Bouret, 2019; Westbrook and Braver, 2015).

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